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Environmental Implications of Service Life Extension of Mobile Devices

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Abstract

The number of mobile Internet-enabled devices (MIEDs) is growing. Producing MIEDs requires resources, energy and causes considerable emissions. Extending the service life MIEDs could significantly reduce the demand for new devices and associated environmental impacts. However, whether service life extension actually reduces environmental impacts associated with MIEDs is still uncertain. First, available life cycle assessments of MIEDs suggest that the production of integrated circuits (ICs) accounts for the majority of GHG emissions during the production phase and that greenhouse gas emissions increase with the size of the device and, more importantly, with its storage capacity. However, there is only little information available on MIED specific components such as logic or memory type integrated circuits. In order to quantify environmental impacts of service life extension of MIEDs new approaches for life cycle inventory modelling (e.g. modular modelling) are required. Second, service life-extending measures are subject to rebound effects, which occur if the number of devices being produced does not fall as expected. Such effects depend on consumer behaviour (e.g. re-spending effects) and the rationalities of involved economic actors. Thus, environmental, behavioural and economic aspects have to be taken into account in order to develop service life-extending measures that entail environmental benefits while being both economically viable and appealing to consumers.

1 Introduction

Mobile Internet-enabled devices (MIEDs) such as smartphones, laptops, and tablets have become an integral part of our everyday life, which is reflected in the large increase in the number of devices sold in recent years [1]. These devices require a considerable amount of resources and energy for their production, during their use and must be disposed at their end-of-life [2].

To date, information and communication technology (ICT) end user devices (including MIEDs) cause more greenhouse gas (GHG) emissions than data centres and telecommunication networks together [3]. Most of the environmental impact throughout the life cycle of MIEDs occurs during production [4]. In particular, their material composition contains more than 50 chemical elements, including several scarce metals [5], whose mining and disposal has toxic impacts on humans and ecosystems.

While specific data on the service life of MIEDs are scarce, it is a common practice to replace MIEDs within a few years, despite the fact they are still functional. Thus, extending the service life of MIEDs is technically feasible and can reduce the demand for newly produced devices and environmental impacts associated with MIED production. However, the service life of MIEDs depends on the actions of many actors, including consumers, producers and retailers. In turn, their actions depend on technological development and the economic and regulatory context (e.g. instalment plans offered by device retailers, availability of secondary markets for used devices, warranty requirements, etc.), and between the actors themselves.

Hence, in order to identify and implement effective measures to extend the service life of MIEDs, it is necessary to systematically investigate related issues from an environmental, behavioural and economic perspective. This paper aims at providing an overview of the current state of knowledge with respect to these perspectives and at exploring approaches and further research needed to tackle them. It is structured as follows: In chapter 2, we provide an overview of the status quo with respect to environmental impacts of MIEDs as well as measures to extend their service life. In order to improve the environmental assessment of measures to extend the service life of MIEDs, we introduce an approach to update life cycle inventory data of mobile devices and discuss environmental impacts of a repair scenario as well as potential indirect effects of service life-extending measures (chapter 3). Finally, we summarize and discuss main findings and provide an overview of challenges that must be addressed in future research (chapter 4).

2 Status Quo

2.1 Assessing the Impacts of MIEDS

Life cycle assessment (LCA) allows to assess the environmental impact of MIEDs and – more specifically – to identify environmental hotspots throughout their life cycle [6]. Several existing LCA studies have focused on specific MIED devices. These include devices such as smartphones (e.g. Sony Ericsson W890 [6], Fairphone 1 [7], Fairphone 2 [8] and Sony Xperia Z5 [9]) and notebooks (e.g. Dell Latitude E6400 [10] and ASUS UL50Ag [11]). Some device manufacturers, such as Apple and HP, also provide information on the GHGs caused throughout the life cycle of their devices [12], [13]. In addition, some articles [14]–[16] provide a comparison of the environmental impacts of different devices.

Figure 1 depicts life cycle-related GHG emissions of various devices. On average, the notebooks cause GHG emissions of 309 kg CO_2 equivalents, the tablets 127 kg CO_2 equivalents, and the smartphones 54 kg CO_2 equivalents. There is considerable variability in the data provided by different studies, which differ in scope and system boundaries. For example, the assumed service life of an MIED has significant influence on the environmental impact per year of use. The results of the LCA studies are therefore not directly comparable. Manhart et al. [15] assume that some studies underestimate total GHG emissions (e.g. Fairphone 1) or those of the manufacturing phase (e.g. iPhone 3G). Similarly, Suckling and Lee [14] assume that the effects of Fairphone 1 are underestimated due to differing assumptions.

Nevertheless, the data suggests that GHG emissions increase with the size of the device and, more importantly, with its storage capacity. This is in line with the observation that GHG emissions per device increase over time due to the increasing complexity and storage capacity of the devices. E.g., a comparison of an Ericsson LCA study from 1995 with a study from 2015 shows that even though the gold content of mobile phones has fallen and batteries have changed from nickel-cadmium batteries to more environmentally friendly lithium batteries, GHG emissions have increased due to the higher complexity and storage capacity [9].

Furthermore, all studies come to the common conclusion that the dominant life cycle phase is the production phase. For this reason, extending the service life of the devices and thus decreasing the need for new devices is most relevant for the reduction of environmental impacts of devices.

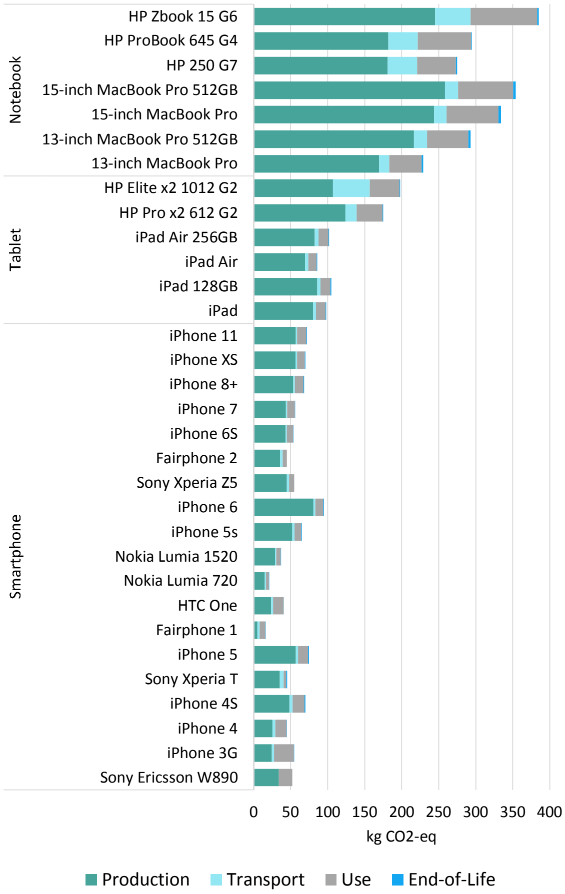

Figure 1: Greenhouse gas emissions (assessed with IPCC 2013 [17]) by life cycle stage of various devices.

Figure 2 shows the GHG emissions caused by the production of main components for three mobile phones (Sony Ericsson W890 [6], Fairphone 2 [8] and Sony Xperia Z5 [9]). The production of the integrated circuits (ICs) accounts for the majority of GHG emissions during the production phase. This effect is mainly due to the use of fossil-based electricity in the manufacturing countries in Asia, because the manufacturing of ICs is a highly energy-intensive process. The ICs consist of processor and memory chips. According to Ercan et al. [9], the GHG emissions caused by the production of the processors (about 4 kg CO_2-eq per cm^2) is higher than for the memory chips (about 3 kg CO_2-eq per cm^2) because the memory production consumes less electricity and has higher yields.

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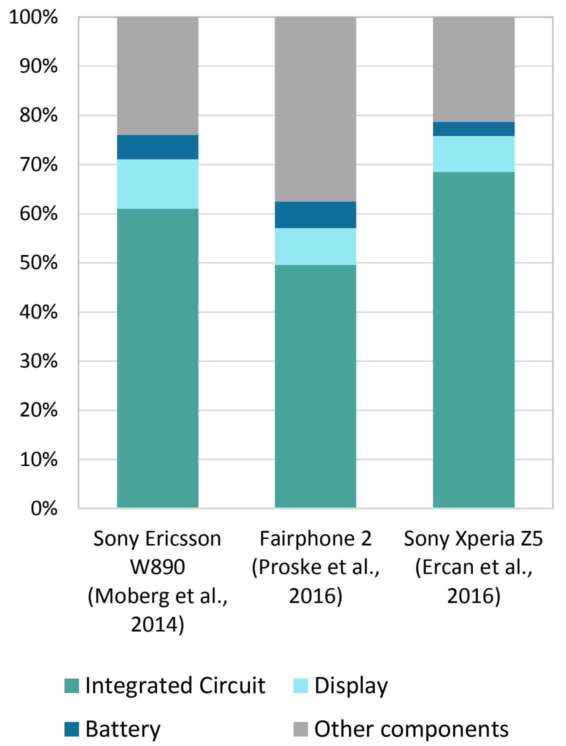

Figure 2: Contribution of different components to the total greenhouse gas emissions caused during production of smartphones (assessed with IPCC 2013 [17]).

Moberg et al. [6] assess the effects of different components in terms of different environmental impact categories for the mobile phone Sony Ericsson W890. For all impact categories, the ICs cause the largest impacts. Again, the effects are mainly due to electricity generation, which is needed for the energy-intensive production of ICs. Ercan et al. [9] also investigate the effects in different impact categories of the Sony Xperia Z5 smartphone. The production stage dominates the impacts in terms of GHG emissions, particulate matter, photo-oxidant creation potential, acidification potential and fresh water eutrophication. The raw material acquisition, in particular gold and copper, cause most of the toxic impacts and the resource depletion.

2.2 Measures for Lifetime Extension of MIEDs

As the production phase dominates the environmental impacts caused throughout the life cycle of MIEDs, extending the average service life of MIEDs (and thus reducing the number of devices produced) seems to be a promising approach to reduce environmental impacts caused by MIEDs. Measures to extend the service life of MIEDs can be clustered into three target categories [18]: The first target is to (1) increase longevity of devices through improved hardware or software. The second is to (2) encourage retention, i.e. increasing the time a device is used by the same user. The third is to (3) promote recirculation, i.e. passing on a device to a different user. A number of different measures can help contributing to one or several of these targets. Table 1 provides an overview of selected measures.

Category	Measure
Improve device design	Avoid software- or hardware-induced obsolescence
	Improve reparability and upgradability
	Improve durability
Retention	Increase awareness for environmental impact of device production
	Increase user attachment to device
	Provide possibilities to repair device
Recirculation	Re-sell device
	Pass on device (e.g. to a family member)
	Device-as-a-service business models
	Repurpose device in different context (e.g. for educational purposes at schools)

Table 1: Selected measures to extend the service life of MIEDs clustered into three categories.

These measures differ in the involvement of and impact on a variety of actors. For example, device design measures lie mainly in the responsibility of organizations involved in the production of MIED hardware and software; however, these face trade-offs when adopting these measures because their revenues correlate with the number of devices produced. Thus, business models, which decouple revenues from the number of devices produced (e.g. renting out instead of selling devices), and policies to incentivize manufacturers to increase service life of devices are required. For example, the EU is considering an initiative to force device manufacturers to use universal mobile phone chargers with a standardized interface [19].

Device retention is mainly shaped by consumer decisions (e.g. when and whether to purchase a new device, repair a broken one, etc.). However, device manufacturers and retailers can also increase device retention, e.g. by offering affordable and convenient repair services or by increasing user attachment to devices through design measures (e.g. engravings). The launch of new device generations and associated marketing activities can have a reducing effect on device retention. Eventually, also the legal framework is important here (e.g. warranty requirements, etc.).

Recirculation measures are again shaped to a large extent by consumer decisions. There must be both a supply of attractive secondary devices as well as a demand for them. Apart from financial considerations and privacy concerns, recirculation is influenced by the availability of convenient ways to pass on a device that is no longer used, e.g. through conveniently located drop-off points [20]) or attractive platforms for re-selling devices.

In many cases, organizations trying to operationalize approaches face challenges. For example, durable and modular smartphones are often larger and heavier than their non-modular counterparts, which is a conflict with demand for compact and lightweight devices [21]. Finding creative solutions requires collaboration of various actors along the MIED value chain, which partly compete with each other. For example, improving modularity of a smartphone can allow new companies to produce spare parts, which were originally only sold and replaced by original equipment manufacturers. Thus, more systematic research allowing to compare the feasibility of various measures is required.

3 Exploring Approaches to Assess Service Life Extension

In the following, we discuss possibilities for assessing environmental impacts of service life-extending measures. This can be seen as a starting point for future research in the field.

3.1 Updated Life Cycle Inventory (LCI) Model for a Smartphone

The availability of life cycle inventory models of MIED specific components is limited. Hischier et al. [22] modelled a smartphone based on data from the ecoinvent database. The production effort for a smartphone is estimated based on available data of production impacts of a laptop computer. In comparison, recently published LCA studies of the production of smartphones show a significant difference in the environmental impact per device. Therefore, we adapted the modular LCI model of Hischier et al. [22] with more recent information on specific components.

3.1.1 Approach

Based on the dataset of Hischier et al. [22], we adjusted the wafer size of the ICs; the weight of the battery, the display, the circuit boards; and also the energy consumption during the production phase. We have modelled the iPhone 6s because Apple has published an environmental report for it [12] and because a teardown report [23] by Chipworks for this device is publicly available. Background data was gathered from the database ecoinvent [24], version 3.5 using the system model "allocation, cut-off by classification".

Since ICs are responsible for the majority of the environmental impact in the production of MIEDs, we paid particular attention to the modelling of ICs. For modelling the ICs of a smartphone, Hischier et al. [22] scaled the weight of a laptop chip to the weight of a mobile chip. However, there are significant differences in the design of ICs used in laptops compared to those used in smartphones. Laptop in contrast to smartphone logic type IC chips, consist of much more IC packaging, which has a lower environmental impact. A smartphone logic type IC chip usually has very little IC packaging, i.e., the chip has almost the same size as the wafer. This is due to the demand for smaller devices with higher performance. Therefore, we increased the surface area of the wafer so that it corresponds to the surface are of a smartphone chip.

In order to adjust the wafer size, we have used the information [23] about the ICs contained in the iPhone 6s. The sum of all logic type IC chips is 6.43 cm^2 [23] per 11 g circuit board [12]. Since smartphone logic type IC chips hardly require any IC packaging, we have made the simplified assumption that the specified area corresponds to the wafer area. The weight of the logic type IC chips and memory type IC chips per circuit board has not been changed. With this information, a wafer area of 0.403 m^2 per kg logic type IC was calculated. This corresponds to an increase of the area by a factor of 22.4, resulting in GHG emissions of 3.45 kg CO_2-eq per cm^2 IC logic type. Manufacturers state that the GHG emissions for processed wafers is in the range of 2.7–4.3 kg CO_2-eq per cm^2 [9]. Thus, our result is within the expected range.

For adjusting the wafer size of the IC of memory type chips, a different approach was chosen. Apple states that the life cycle of the iPhone 6s with 32 GB memory has GHG emissions of 54 kg CO_2-eq and with 128 GB a GHG emissions of 61 kg CO_2-eq. Thus, extending the memory capacity by 96 GB increases the GHG emissions by 7 kg CO_2-eq. Therefore, we assume that manufacturing an IC of memory type with 32 GB memory capacity causes 2.33 kg CO_2-eq. Consequently, we increased the wafer area of the memory type IC until this target value was reached. This resulted in a wafer area of 0.042 m^2 per kg IC of memory type.

In the Environmental Report of the iPhone 6s, the weight of the components circuit boards is stated as 11 g, the display as 29 g and the battery as 26 g [12]. Furthermore, it is stated that the iPhone 6s contains 25 g aluminium, 24 g stainless steel, 18 g glass and 7 g plastic [12]. We adapted the LCI model of Hischier et al. [22] according to these specifications.

For reflecting the target GHG emissions of 43.2 kg CO_2-eq for the production of an iPhone 6s (with 32 GB) [12], we assumed that the remaining difference to the target value of 43.2 kg CO_2-eq is caused by electricity use. This resulted in additional electricity use of 14.3 kWh. This simplification is intended to cover the effects of other aspects that have not been taken into account yet, such as the amount of gold used. In our future work, we will look into these aspects and gradually replace this additional consumption of electricity.

3.1.2 Result and Interpretation

Existing studies (see Section 2.1) suggest that the environmental impact of MIEDs increases with higher device complexity. This is because the memory chip, the CPU, and the graphics chip have the greatest effect on the GHG emissions in the production of the device. For this reason, we have put our focus on updating the LCI for ICs used in smartphones.

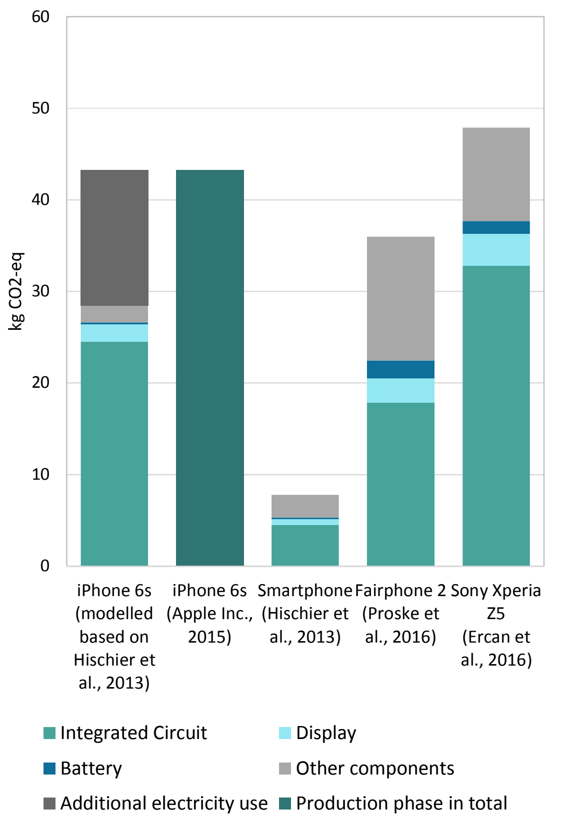

Figure 3: Updated iPhone 6s model in comparison with results from published LCA studies: Greenhouse gas emissions (according to IPCC 2013 [17]) of the production phase per module.

Figure 3 shows the GHG emissions of the production phase per module of the updated model of the iPhone 6s in comparison with the original iPhone 6s [12], the initial model according to Hischier et al. [22] and other results from published LCA studies [8], [9]. It can be seen that the share of the production of the ICs of the total device is within an expected range. The GHG emissions of the IC production of published LCA studies is between 50% and 68% of the total production phase, in the case of the modelled iPhone 6s it is 57%. It can be concluded that adjusting the wafer area is a reasonable approach for updating the LCI of smartphones. The GHG emissions of the displays are also within the expected range.

In future work the modelling of memory ICs has to be examined more closely. Up to now, the wafer size has been adjusted, but other parameters of the memory chips should also be considered. Besides, the GHG emissions of the battery of the modelled iPhone 6s are below the expected proportion. It is therefore required to examine the battery production in more detail. The electricity used in the production of the individual components and the amount of gold built in the components must be investigated, as these are the primary sources of GHG emissions. In this way, the additionally added electricity consumption could be replaced or allocated to the individual components.

It should also be noted that the approach for updating the LCI model presented in section 3.1.1 describes a starting point for updating LCI models for smartphones. Therefore, this approach contains uncertainties and has to be further improved in future work. For example, information on the IC package area was used to adjust the wafer area, instead of considering the actual die dimensions. Therefore, the next step is to model a recent smartphone for which a detailed teardown report, including the die area, is available.

3.2 Assessment of a Repair Scenario

In order to quantify the environmental impacts caused by the service life-extending measure “repair”, we calculated a repair scenario of an exemplary smartphone, which was in this case the iPhone 8 [23].

Since the display and battery are often replaced during a repair, we have considered a replacement of the battery and the display in our repair scenario. As shown in section 2.1, GHG emissions from battery production account for up to 5% of total emissions of the production phase. The production of the display accounts for up to 10 % of the total emissions of the production phase.

For investigating the impact of the transport required for the smartphone’s repair, we calculated the environmental impacts using a lorry process from the ecoinvent database version 3.5 using the system model “allocation, cut-off by classification” [24]. A transport from Switzerland to Poland with a distance of 1,000 km (2’000 km in total including the return trip) was assumed. The calculated GHG emissions for the transport to Poland only account for about 1% of the GHG emissions of the production of a new display.

Figure 4 compares the GHG emissions of the repair scenario with GHG savings due to a possible avoided production of a new device. In both cases, the use phase is assumed to be 2 years.

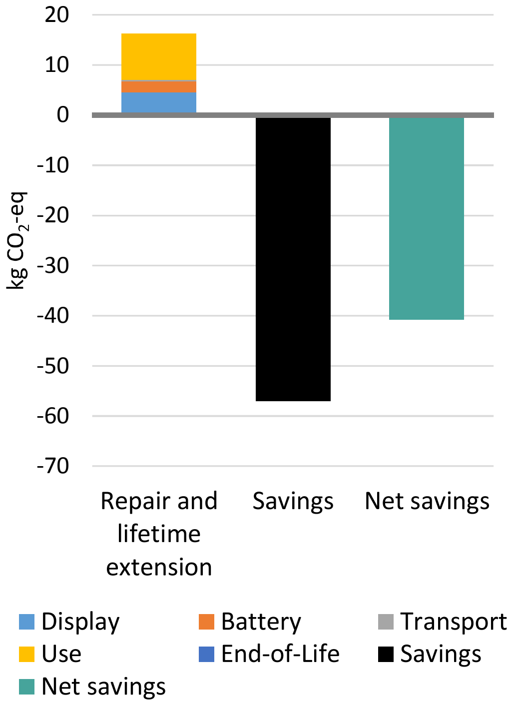

Figure 4: Greenhouse gas emissions (assessed with IPCC 2013 [17]) of a new device in comparison to the repair scenario.

Assuming the service life is extended from 2 years to 4 years and the display and the battery are replaced after 2 years, 72% of the GHG emissions of a new device can be saved compared to buying a new device every two years. This is because the main environmental impacts are caused by the ICs that are not replaced in the repair scenario.

Therefore, we can conclude that the extension of the service life by replacing a battery or a display is worthwhile in terms of GHG emissions, despite the additional emissions from the production of new components and transportation.

3.3 Indirect Effects of Service Life-extending Measures

The main target of measures to extend the service life of MIEDs is to reduce the number of devices produced and associated environmental impacts. However, indirect effects (e.g. rebound effects) can counterbalance environmental gains from service life-extending measures.

Tamar and Makov [26] discuss two rebound mechanisms of service life-extending measures of smartphone: *Imperfect substitution* occurs when extending the service life of a used device "does not avoid demand and production of new product units on a 1:1 basis" [26, p. 2]. *Re-spending effects* occur if used devices, parts or materials are cheaper than their new counterparts, leading to an increase in effective income of consumers who purchase other goods or services, which are also associated with environmental impacts. A flourishing market for used MIEDs can even stimulate market growth, e.g. because consumers can easily sell their devices and invest the income into new devices [26], [27]. Some users, who would not have purchased a new device at all, might purchase a used device because it costs less [26]. The results of the analysis of Makov and Font Vivanco shows that in the US imperfect substitution and the re-spending effect lead to rebound effect between 27% and 46% for specific smartphone models and can even exceed 100% (backfire) in specific regions and under different consumer behaviour.

Service life-extending measures can also lead to induction effects, which occur if adopting the measures induces activities, which are associated with environmental impacts (e.g. consumers traveling to repair facilities or additional connectors required in modular smartphones). Exporting devices for re-use in developing countries can also cause environmental impacts beyond energy consumption and GHG emissions, because these devices, at their end-of-life, are often informally recycled with toxic impacts on the environment and humans [28].

Thus, whether or not a service-life-extending measure leads to reduction of environmental impacts of MIEDs depends largely on the extent to which a measure increases the service life of a device or its components, and thereby avoids additional production, as well as associated rebound and induction effects.

4 Discussion and Conclusion

As the production of ICs causes the highest environmental impacts throughout the service life of an MIED, extending the service life of an MIED is a promising approach to reduce environmental impacts caused by MIEDs. Several measures to extend the service life have been explored in academia and industry practice, which can be clustered into measures, which aim at improving the device design, at device retention and device recirculation. We assessed environmental impacts of a repair measure and showed that the production of new devices causes more than two times more GHG emissions than extending the service life of an existing device by replacing the display and the battery.

However, indirect effects (such as rebound effects) can compensate for environmental gains from lifetime extending measures. For example, it is unclear to what extent the extension of the service life of an MIED

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actually avoids the production of a new device. Also, re-using devices might trigger additional consumption (e.g. for accessories) or the availability more affordable – used – devices can induce consumers to replace their existing device earlier than later. These effects depend on the behaviour of individual consumers and complex supply and demand relationships in the MIED market.

Thus, environmental, behavioural and economic aspects have to be taken into account in order to develop service life-extending measures that entail environmental benefits while being both economically viable and appealing to consumers. To successfully implement measures to achieve service life extension, economically viable business models, which have environmental benefits and are socially accepted, are required in order to incentivise a more sustainable use of MIEDs.

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6 Literature

[1] L. Belkhir and A. Elmeligi, 'Assessing ICT Global Emissions Footprint: Trends to 2040 & Recommendations', *J. Clean. Prod.*, vol. 177, pp. 448–463, Mar. 2018, doi: 10.1016/j.jclepro.2017.12.239.

[2] J. C. T. Bieser and V. C. Coroamă, 'Direkte und indirekte Umwelteffekte der Informations- und Kommunikationstechnologie', *Sustain. Manag. Forum Nachhalt.*, Jun. 2020, doi: 10.1007/s00550-020-00502-4.

[3] J. Bieser, R. Hintemann, S. Beucker, S. Schramm, and L. Hilty, 'Klimaschutz durch digitale Technologien – Chancen und Risiken', Bitkom e. V., Berlin, Kurzstudie, 2020. [Online]. Available: https://www.bitkom.org/klimaschutz-digital.

[4] R. Keller, M. Stucki, and R. Itten, 'Projekt Digitale Suffizienz - Ökobilanzbericht zur Nutzung digitaler Geräte durch Jugendliche in der Schweiz', Institut für Umwelt und Natürliche Ressourcen ZHAW, Wädenswil, Jun. 2019.

[5] P. A. Wäger, R. Hischier, and R. Widmer, 'The Material Basis of ICT', in *ICT Innovations for Sustainability*, vol. 310, L. M. Hilty and B. Aebischer, Eds. Cham: Springer International Publishing, 2015, pp. 209–221.

[6] Å. Moberg *et al.*, 'Simplifying a life cycle assessment of a mobile phone', *Int. J. Life Cycle Assess.*, vol. 19, no. 5, pp. 979–993, May 2014, doi: 10.1007/s11367-014-0721-6.

[7] M. Güvendik, 'From Smartphone to Futurephone. Assessing the Environmental Impacts of Different Circular Economy Scenarios of a Smartphone Using LCA', Universiteit Leiden, 2014.

[8] M. Proske, C. Clemm, and N. Richter, 'Life Cycle Assessment of the Fairphone 2', Fraunhofer IZM, Berlin, Final Report, November 2016, Nov. 2016.

[9] M. Ercan, J. Malmodin, P. Bergmark, E. Kimfalk, and E. Nilsson, 'Life Cycle Assessment of a Smartphone', presented at the ICT for Sustainability 2016, Amsterdam, the Netherlands, 2016, doi: 10.2991/ict4s-16.2016.15.

[10] S. O'Connell and M. Stutz, 'Product carbon footprint (PCF) assessment of Dell laptop - Results and recommendations', in *Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology*, Arlington, VA, USA, May 2010, pp. 1–6, doi: 10.1109/ISSST.2010.5507731.

[11] J. Franze, *LCA of an Ecolabeled Notebook – Consideration of Social and Environmental Impacts Along the Entire Life Cycle*. Berlin: Lulu Com, 2011.

[12] Apple Inc., 'iPhone 6s Plus Environmental Report', Environmental Status Report, 2015. Accessed: Oct. 04, 2019. [Online]. Available: https://www.apple.com/th/environment/pdf/products/iphone/iPhone6sPlus_PER_sept2015.pdf.

[13] HP Development Company, L.P., 'Product Carbon Footprint HP 250 G7 Notebook PC', Product Carbon Footprint Reports, 2019. Accessed: Oct. 04, 2019. [Online]. Available: https://h22235.www2.hp.com/hpinfo/globalcitizenship/environment/productdata/Countries/_MultiCountry/productcarbonfootprint_notebo_201931323854209.pdf.

[14] J. Suckling and J. Lee, 'Redefining Scope: The True Environmental Impact of Smartphones?', *Int. J. Life Cycle Assess.*, vol. 20, no. 8, pp. 1181–1196, Aug. 2015, doi: 10.1007/s11367-015-0909-4.

[15] A. Manhart *et al.*, 'Resource Efficiency in the ICT Sector', Greenpeace e.V.; Öko-Institut e.V., Freiburg, DE, Final Report, November 2016, Nov. 2016. Accessed: Dec. 29, 2016. [Online]. Available: https://www.greenpeace.de/sites/www.greenpeace.de/files/20161121_oeko_resource_efficency_final_zusammenfassung.pdf.

[16] P. Teehan and M. Kandlikar, 'Comparing Embodied Greenhouse Gas Emissions of Modern Computing and Electronics Products', *Environ. Sci. Technol.*, vol. 47, no. 9, pp. 3997–4003, May 2013, doi: 10.1021/es303012r.

[17] IPCC, 'Climate Change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change', Cambridge University Press, 2013. [Online]. Available: http://www.climatechange2013.org/images/report/WG1AR5_ALL_FINAL.pdf.

[18] M. Jobin, C. Külling, M. Jattke, and Y. B. Blumer, 'Extending the lifetime of mobile devices to reduce their environmental impact: a glimpse on the project LIFESAVING', *SocietyByte*, May 20, 2020. https://www.societybyte.swiss/2020/05/20/extending-the-lifetime-of-mobile-devices-to-reduce-their-environmental-impact-a-glimpse-on-the-project-lifesaving/ (accessed Jul. 09, 2020).

[19] M. Khan, 'EU seeks to force through single standard phone charger', *Financial Times*, 2020. https://www.ft.com/content/65a2dd48-4140-11ea-bdb5-169ba7be433d (accessed Jun. 07, 2020).

[20] P. Tanskanen and E. Butler, 'Mobile phone take back learning's from various initiatives', in *Proceedings of the 2007 IEEE International Symposium on Electronics and the Environment*, May 2007, pp. 206–209, doi: 10.1109/ISEE.2007.369395.

[21] W. B. Wilhelm, 'Encouraging Sustainable Consumption through Product Lifetime Extension: The Case of Mobile Phones', *Int. J. Bus. Soc. Sci.*, vol. 3, no. 3, 2012, Accessed: Jun. 06, 2020. [Online]. Available: /paper/Encouraging-Sustainable-Consumption-through-Product-Wilhelm/10f330f69fee1c3373f9cc4e1bdce381e7598c5d.

[22] R. Hischier, M. Keller, L. Hilty, and R. Lisibach, 'mat - an ICT application to support a more sustainable use of print products and ICT devices', 2013, doi: 10.5167/uzh-84885.

[23] Chipworks Inc., 'Apple iPhone 6s Complementary Teardown Report with Additional Commentary', Chipworks Inc., Ottawa, Ontario, Canada, Oct. 2015. Accessed: Jun. 15, 2020. [Online]. Available: https://www.researchgate.net/publication/320906509_Positioning_Techniques_with_Smartphone_Technology_Performances_and_Methodologies_in_Outdoor_and_Indoor_Scenarios/fulltext/5a01bb27a6fdcc232e2eb914/Positioning-Techniques-with-Smartphone-Technology-Performances-and-Methodologies-in-Outdoor-and-Indoor-Scenarios.pdf.

[24] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, 'The ecoinvent database version 3 (part I): overview and methodology', *Int. J. Life Cycle Assess.*, vol. 21, no. 9, pp. 1218–1230, Sep. 2016, doi: 10.1007/s11367-016-1087-8.

[25] Apple Inc., 'iPhone 8 Environmental Report', Environmental Status Report, 2017. Accessed: Oct. 04, 2019. [Online]. Available: https://www.apple.com/environment/pdf/products/iphone/iPhone_8_PER_sept2017.pdf.

[26] T. Makov and D. Font Vivanco, 'Does the Circular Economy Grow the Pie? The Case of Rebound Effects From Smartphone Reuse', *Front. Energy Res.*, vol. 6, 2018, doi: 10.3389/fenrg.2018.00039.

[27] D. R. Cooper and T. G. Gutowski, 'The Environmental Impacts of Reuse: A Review', *J. Ind. Ecol.*, vol. 21, no. 1, pp. 38–56, 2017, doi: 10.1111/jiec.12388.

[28] E. A. Yu, M. Akormedi, E. Asampong, C. G. Meyer, and J. N. Fobil, 'Informal processing of electronic waste at Agbogbloshie, Ghana: workers' knowledge about associated health hazards and alternative livelihoods', *Glob. Health Promot.*, vol. 24, no. 4, pp. 90–98, Dec. 2017, doi: 10.1177/1757975916631523.